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Lystrup, Aage

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Hybrid yarn for thermoplastic fibre composites.
Summary of technical results

Final report for MUP2 Framework Program No. 1994-503/0926-50

Aage Lystrup, Tom Løgstrup Andersen, Hans Knudsen, Torben Vestergaard, Lars Lilleheden, Jørgen Vestergaard

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INTRODUCTION

There is a big interest in fibre composite materials with thermoplastic polymer matrix, because the thermoplastic polymers (compared with thermosetting polymers) offer a potential for a greater fracture toughness, larger elongation at fracture, faster and more automatic processing, unlimited shelf life of the raw material, recycling, and a more clean working environment because no organic solvents are involved in the workshop processes. The legislation on e.g. styrene concentration becomes more and more strict. Therefore, the continuous struggle and the big investment necessary to continuously lower the styrene concentration in the traditional glass fibre industry will disappear, if unsaturated polyester is substituted with a thermoplastic polymer.
With the increasing interest in using thermoplastic fibre composites with continuous fibres, there is also an increasing demand for development of new materials and knowledge and basic understanding of processing technology for these new materials. The most important differences in the production technology of fibre composites with thermoplastic matrices compared with composites with thermosetting matrices arise from the much higher viscosity and higher processing temperature of the thermoplastic composites. The melt viscosity of the thermoplastic matrices is as high as 100-1000 Pa× s, which means that it is difficult for the molten plastic to penetrate the fibre bundles and ensure a complete wetting of all individual fibres. In comparison, the viscosity of thermosetting matrices used for fibre composites is in the range of 0.1-10 Pa× s.

A new type of hybrid yarn for production of fibre composites with thermoplastic matrix material is developed and tested. A hybrid yarn is a commingled textured yarn consisting of structural fibres and thermoplastic fibres. In a subsequent heating and consolidation process the plastic fibres melt and become the matrix material in the formed fibre composite material. The hybrid yarn is a so called postpreg material (opposite prepreg) since the fibres are impregnated with the matrix in a post-process. The hybrid yarn is "soft" and drapeable, and therefore very suitable for producing fibre preforms by almost any textile technology. It is essential for the ease of production of components that the hybrid yarn is a thorough and homogenous mixture (on the fibre level) of the two types of fibres. When the fibres are well mixed, the flow distance of the molten matrix is little, which means that the time at temperature may be short, and/or the consolidation pressure may be little.

Two types of processing technology are developed and studied: Vacuum consolidation and press consolidation. Vacuum consolidation of hybrid yarn fabrics is suitable for fabrication of larger parts such as wind turbine blades, and press consolidation is a fast process suitable for smaller parts such as automobile body parts.

To demonstrate the potential for industrial use of the developed hybrid yarn and process technologies a section of a wind turbine blade, an inspection cover and a car door-post have been produced.

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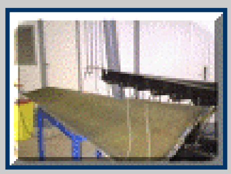
WIND TURBINE BLADE

To test and demonstrate the potential of using the developed hybrid yarn for production of wind turbine blades a complete 1.5 m long blade and a 3.2 m long section of a blade have been manufactured by a developed vacuum consolidation technique.
The material used for the wind turbine blades is a non-crimp stitched fabric produced from a hybrid yarn mixed of glass fibres and modified PET fibres. (PET = polyethyleneterephtalate) The fabrics are stacked at the mould into a laminate with the desired thickness and fibre orientation, vacuum bagged, evacuated, heated to the process temperature (225 °C for the modified PET), and finally cooled back to room temperature to be consolidated into a solid laminate. The thickness of the 3.2 m long blade section is tapered along the length from 23 mm to 12 mm.

Two different mould concepts are also tested. A composite mould for the 1.5 m long blade is constructed from glass fibre/epoxy prepreg, and a metal mould for the 3.2 m long section is build from shaped and welded steel plates.

In general, high material quality (that is high fibre content (40 vol.-%), low porosity (< 2 vol.-%) and controlled fibre orientation) is obtained in both test blades, and the vacuum consolidation technique is a very clean and a robust process. Therefore, the developed hybrid yarn is considered to have great potential for future production of wind turbine blades, although many aspects, such as root end attachment, joining between air foils and spars, and surface protection, still need to be address and solved.

1.5 m long wind turbine blade produced in thermoplastic composites from the hybrid yarn.



3.2 m long section of a thermoplastic composite shell for a wind turbine blade. The steel mould for the shell is shown in the back.

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INSPECTION COVER FOR A WIND TURBINE BLADE

A cover for an inspection hole of a wind turbine blade is produced from the hybrid yarn by a developed press consolidation technique.

The material used for the cover is a balanced woven fabric produced from a hybrid yarn mixed of glass fibres and PET fibres.

Inspection cover in thermoplastic composites for a wind turbine blade. The cover is press consolidated from hybrid yarn fabric.

The fabrics are stacked into a laminate with the desired thickness, heated to the process temperature (290-300 °C for the PET), transferred to the press mounted with a cold pressing tool, and finally pressed and consolidated into shape.
The pressing tool is a match die type, and both the upper and lower pressing tool are made of Aluminium.

The inspection cover measures 390 x 180 mm, and because it has a rather simple geometry it was used to run in and tune the press consolidation technique on the industrial press line developed and constructed within the program. The final inspection covers are manufactured using a pressing force of 1000 kN and a pressing time of only 50 seconds. The components are produced with repeatable accuracy and high material quality. Inspection covers will be mounted on blades on wind turbines in service to test and evaluate the weather and erosion resistance of the thermoplastic composite material as fabricated (no additional surface treatment). These information will be very useful for designing future wind turbine blades in thermoplastic composites.

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CAR DOOR-POST

A car door-post is produced from the hybrid yarn by a developed press consolidation technique.

A car door-post press consolidated in thermoplastic composites from hybrid yarn fabric.

The material used for the door-post is a balanced woven fabric produced from a hybrid yarn mixed of glass fibres and PET fibres.

The fabrics are stacked into a laminate with the desired thickness, heated to the process temperature (290-300 °C for the PET), transferred to the press mounted with a cold pressing tool, and finally pressed and consolidated into shape.

The prototype pressing tool for the door-post consists of a glass fibre/epoxy female mould and a silicone rubber male mould. The female mould is manufactured by wet hand lay-up of glass fibre/epoxy on a model of an existing steel door-post, and the male mould is cast in silicone rubber inside the female mould. Before casting the male mould, the surface of the female mould is covered with a layer of wax plates to create a space between the two moulds to form the wall thickness during pressing of the final part.

Manufacturing of the door-post has with success been used to test the production of components with rather complex geometry on the industrial press line developed and constructed within the program. The final car door-posts are manufactured using a pressing force of 900 kN and a pressing time of only 12 seconds. The quality of the material of the fabricated part has been examined, and it shows a well consolidated material with a fibre content of 45 vol.-% and a porosity of app. 2 vol.-%.

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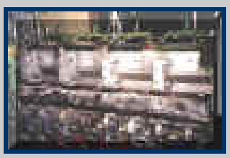
AIR TEXTURING OF THE HYBRID YARN

Four texturing machines are modified/changed into research texturing machines in order to investigate and develop the air texturing technology for glass fibre roving. The texturing machines are used to commingle (at fibre level) the glass fibres and the polymer fibres. The machines are changed/modified at the following points: New types of air texturing nozzles, multiple feed of glass fibre roving, more simple threading through the machines to minimise fibre damages, and devices to "loosen" the fibres, which are held together by the sizing (surface treatment).
The texturing technology is developed to a stage where it is possible to air texture glass fibre roving with up to a size of 600 Tex together with polymer fibres, and fabricate laminate of high quality from the textured hybrid yarn. The quality of the textured yarn depends strongly on both the type and the amount of sizing on the glass fibres.



Four texturing machines modified for texturing of thick glass fibre roving.

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MATERIALS AND MECHANICAL PROPERTIES

Several candidates of glass fibre roving and polymer fibres have been tested and characterised in order to identify the optimum combinations. Two combinations of glass fibres and polymer fibres were selected for the development of the hybrid yarn. A 300 Tex glass fibre roving with a special developed sizing is used in both combinations, but two different types of polymer fibres, also special developed, are used for the hybrid yarns. The one type of polymer fibres is PET (polyethyleneterephtalate), and the other type is a modified PET with a lower melting and processing temperature. The processing temperature for the hybrid yarn based on PET is 280-300 °C, and for the modified PET based hybrid yarn, the processing temperature is 220-240 °C.
Composite laminates consolidated form the hybrid yarn have excellent room temperature tensile properties. Both filament wound unidirectional laminates and laminates consolidated from balanced woven fabrics (Twill 3/3) have been evaluated and characterised. All the laminates have a porosity lower than 1 vol.-%, a fibre content of 41 vol.-% and 44 vol.-% for the modified PET laminates and the PET laminates, respectively, and room temperature tensile and shear properties as shown in the table.

TENSILE AND SHEAR PROPERTIES OF COMPOSITE LAMINATES CONSOLIDATED FROM HYBRID YARN

	Unidirectional						Woven fabric	
	0°-direction		90°-direction		12° Off-axis		Balanced Twill 3/3	
	Mod. PET	PET	Mod. PET	PET	Mod. PET	PET	Mod. PET	PET
E-modulus [GPa]	32	35	8	10	-	-	20	22
Strength [MPa]	580	520	45	55	50	60	280	260

The high bonding strength between the fibres and the matrix material is reflected by the high shear strength of the laminates, which is, respectively, 50 MPa and 60 MPa for the modified PET and the PET matrices, measured by 12° off-axis shear tests on unidirectional laminates.
The mechanical properties of woven fabric laminates have also shown to be unaffected by the following accelerated weather ageing process:

Cycle:	8 hours of ultra violet radiation at 70 °C followed by 4 hours of condensation at 50 C° and 100% relative humidity.
Time:	120 hours (10 cycles)
UV-source:	UVB-313 with top emission of 313 nm

Equipment: QUV, Cyclic Ultraviolet Weathering Tester from Q-Panel Company.

Micro structure of a glass fibre/PET laminate consolidated from hybrid yarn fabrics showing perfect wetted fibres and no porosity.

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PRESS CONSOLIDATION OF HYBRID YARN FABRICS

Press consolidation of thermoplastic composites is a very fast process which is suitable for production of smaller components in larger series. In principal, the process consists of four steps: 1) Heating the material to the process temperature, 2) transfer the heated material to the press, 3) shape, consolidate and cool the material in the press, and 4) remove the finished part from the press.

A new prototype industrial press line has been designed and constructed. The equipment consists of three heating units (stations), a material transport system for automatic production, and the press itself. The press is a double acting hydraulic press with a maximum press force of 1000 kN and a press area of 700 x 700 mm2.
Also, a new research press facility has been designed and built. The equipment consists of a press, a material transport arrangement, a PC/PLC control unit, and a process data sampling unit. The press is a single active hydraulic press with a maximum press force of 200 kN and a maximum press area of 1000 x 800 mm. At the heating station the material is heated under vacuum to prevent/minimise the degradation of the thermoplastic matrix material prior to press forming of the laminates. The advanced process control and data sampling system regulates all process parameters: Process temperature, vacuum, speed of material transportation, speed of pressing, pressing pressure or position of the pressing tool, and the pressing time.

Optimising of the press consolidation technique for the developed hybrid yarn has been performed on balanced woven fabric of glass/PET, showing that it is a very robust process where high material quality (fibre content 45 vol.-%, porosity < 2 vol.-%, no unwetted fibres) is obtained for a large process window. The optimum for a 2 mm thick laminate is achieved with the following process parameters: A preheating temperature of 300 °C, preheating under vacuum, a preheating time of 12 minutes, a press tool temperature of 75 °C, a consolidation pressure of 0.8 MPa, and a press time of 15 seconds.

Research press facility for press consolidation of thermoplastic composites.

Industrial press line for press consolidation of thermoplastic composites.

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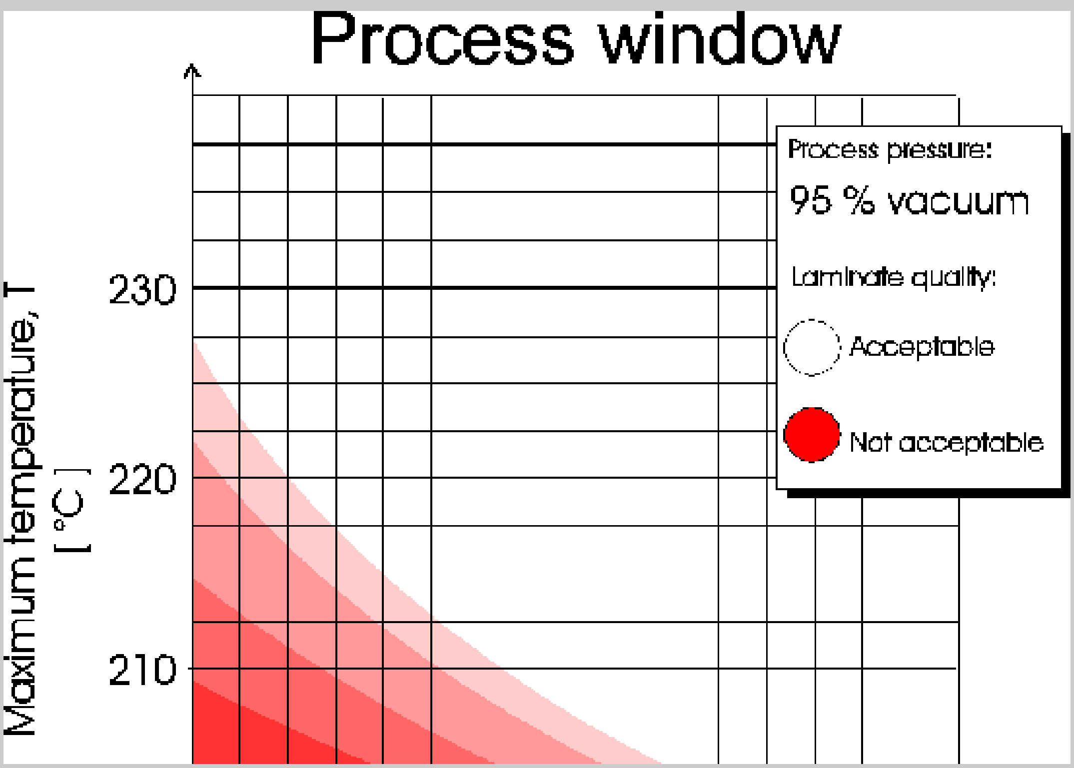
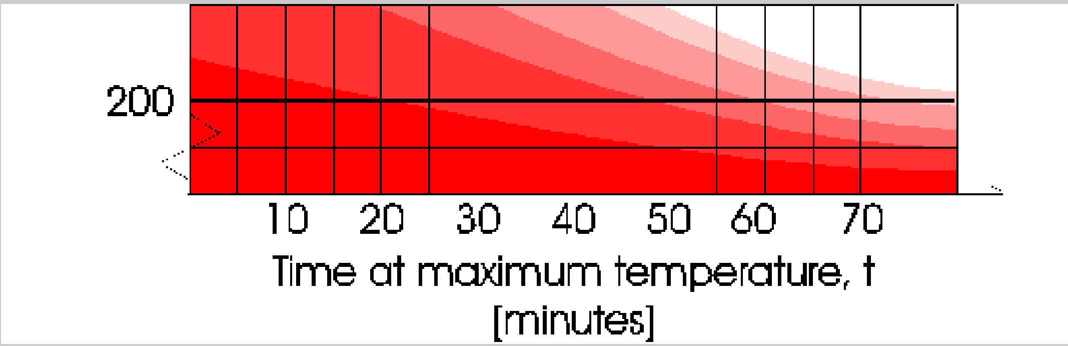
VACUUM CONSOLIDATION OF HYBRID YARN FABRICS

Vacuum consolidation of thermoplastic composites is suitable for production of small to very large components in smaller series. In principal, the process consists of four steps: 1) Lay-up the hybrid yarn fabric into the mould, 2) vacuum bag and evacuate the material, 3) heat the material and the mould to the process temperature under vacuum, and 4) cool it all back to room temperature. The process temperature can either be obtained by built-in heating elements in the mould or by heating the entire mould in an oven, and therefore, there are practically no limits on the size of the components which can be produced.

The vacuum consolidation process has been developed and optimised for the hybrid yarn material, and the process window for glass fibre/modified PET hybrid yarn fabric has been examined by varying the process temperature, the time at temperature, and the vacuum level. It is possible to obtain an acceptable laminate quality by using a process temperatures as low as 210 °C. However, the lower the temperature the longer time at temperature is required. The time at temperature can be as low as 12 minutes, if high temperature and full vacuum are used. Furthermore, a vacuum level of only 65% of full vacuum is sufficient if high temperature and long time at temperature are utilised.
It is concluded that the vacuum consolidation technique is a very robust process with a large process window, and therefore very suitable and attractive for industrial use; even in a crude workshop environment.





Process window for vacuum consolidation of thermoplastic composites from hybrid yarn fabric.

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ENVIRONMENTAL EVALUATION OF HYBRID YARN COMPOSITES

An environmental evaluation of the manufacture of hybrid yarn and composites hereof has been done. As guidelines the structure of ISO 14040 and UMIP have been used. Regarding the working environment, the only recommendation is to use gloves, compared with normal working recommendations.

One conclusion is that there are no big environmental problems. For the production only plentifully natural resources are used, with crude oil as the most problematic resource. Another conclusion is that use of the hybrid yarn is a gain for the environment, compared to the use of thermosetting polymers, because the thermoplastic polymers can be reused far more easy.

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PROGRAM PARTNERS AND CONTACTS

The framework program has the following partners and contact persons:

Partner	Contact person
A/S Kaj Neckelmann P.O. Box 319 DK-8600 Silkeborg Denmark	Name: Hans Knudsen, M.Sc. Phone: +45 8922 3437 Fax: +45 8681 5833 hans.knudsen@neckelmann.dk
Komposit Procesteknik ApS Skaldhøjvej 12 DK-8981 Spentrup Denmark	Name: Torben Vestergaard, B.Sc. Phone: +45 8647 9277 Fax: +45 8647 7788 TorbenVestergaard@composit.dk
LM Glasfiber A/S Rolles Møllevej 1 DK-6640 Lunderskov Denmark	Name: Lars Lilleheden, M.Sc.,ph.d. Phone: +45 7558 5122 Fax: +45 7558 6202 ll@lm.dk http://www.lm.dk/
Risø National Laboratory Materials Research Dept. P.O. Box 49 DK-4000 Roskilde Denmark	Name: Aage Lystrup, B.Sc., Program manager Phone: +45 4677 5775 Fax: 45 4677 5758 aage.lystrup@risoe.dk